Calorimetry

Lecture 1

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FERMILAB-CERN
HADRON COLLIDER PHYSICS
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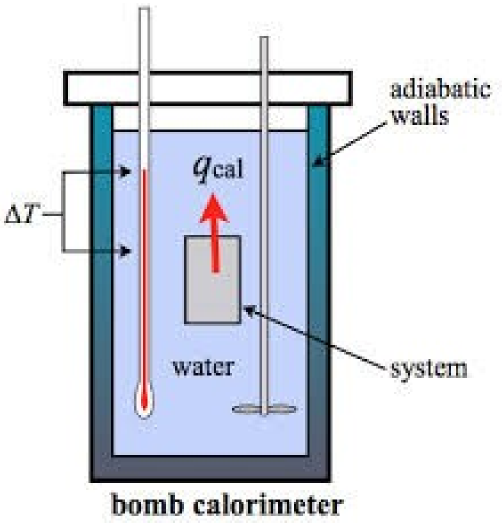
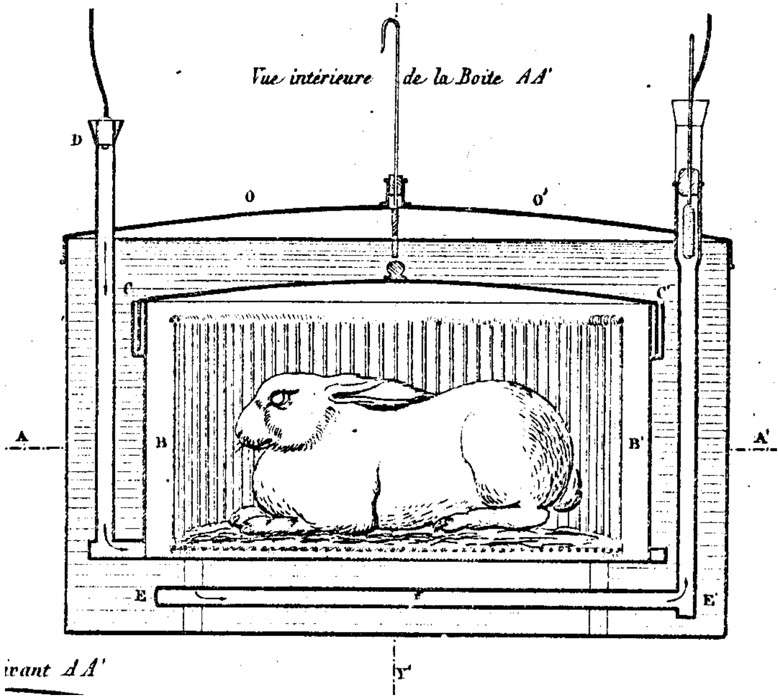
Outline

- Calorimeters in Context: Why Calorimetry?
- Principles of Calorimetry
  - Interactions with matter
  - Shower shapes and cascades
- Types of Calorimeters
  - Total Absorption, Sampling
  - Scintillation, Ionization, Cherenkov
  - Signal Detection

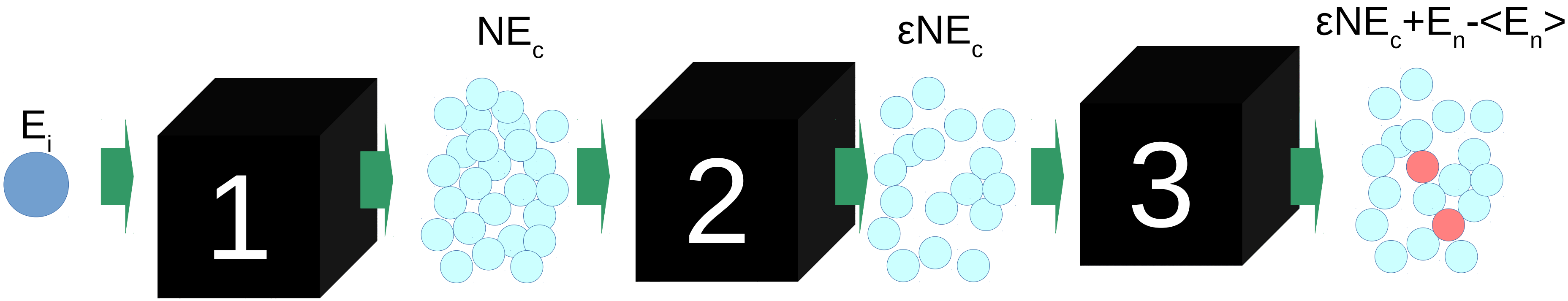
What is Calorimetry Really?

- The first calorimeter which you probably met as a student was a “bomb” calorimeter
  - Measure the temperature change of a known volume of water to determine the energy released in a reaction – sharing the reaction energy with many molecules evenly to determine the total
- HEP Calorimetry has similarities
  - Convert the energy of an incoming single particle into many lower-energy particles and count the number of particles to determine the original total





Abstract Calorimetry



$$E_m = \epsilon N E_c + E_n - \langle E_n \rangle$$

$$\sigma_{E_m} = \sigma_\epsilon N E_c \oplus \epsilon \sigma_N E_c \oplus \sigma_n$$

$$\sigma_{E_m} = \sigma_\epsilon N E_c \oplus \epsilon \sqrt{N} E_c \oplus \sigma_n$$

$$\frac{\sigma_{E_m}}{E_m} = \frac{\sigma_\epsilon N E_c}{\epsilon N E_c} \oplus \frac{\epsilon \sqrt{N} E_c}{\epsilon N E_c} \oplus \frac{\sigma_n}{\epsilon N E_c}$$

$$\frac{\sigma_{E_m}}{E_m} = \frac{\sigma_\epsilon}{\epsilon} \oplus \frac{\sqrt{\epsilon E_c}}{\sqrt{E_m}} \oplus \frac{\sigma_n}{E_m}$$

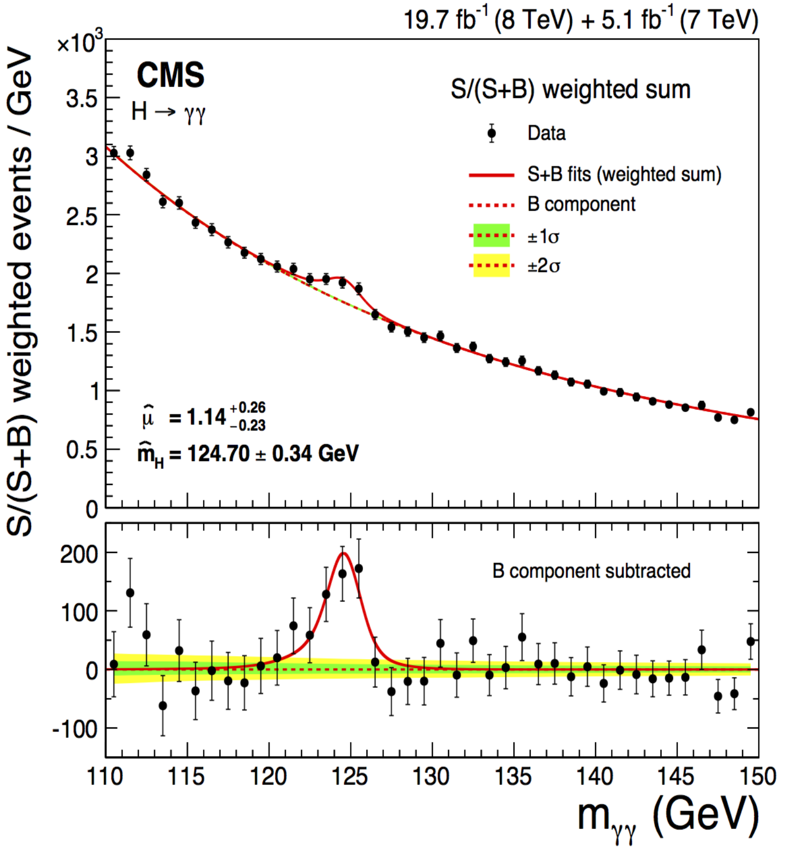
$$\frac{\sigma_{E_m}}{E_m} = \frac{a}{E_m} \oplus \frac{b}{\sqrt{E_m}} \oplus c$$

Why Calorimetry?

- Particles have high momentum and can be collected by calorimetry
  - Poor targets for calorimetry : μ ν
- Particles do not have electric charge and therefore do not bend in magnetic fields or leave signals in tracking detectors
  - Poor targets for tracking : γ n K_L ν

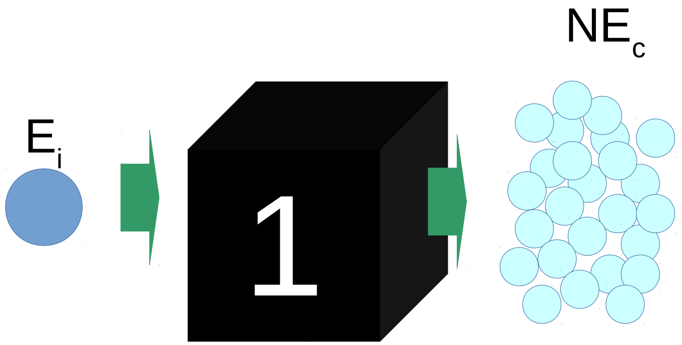
$$\frac{\sigma_E}{E} = \frac{a}{E} \oplus \frac{b}{\sqrt{E}} \oplus c$$

$$\frac{\sigma_p}{p} = a\,p$$

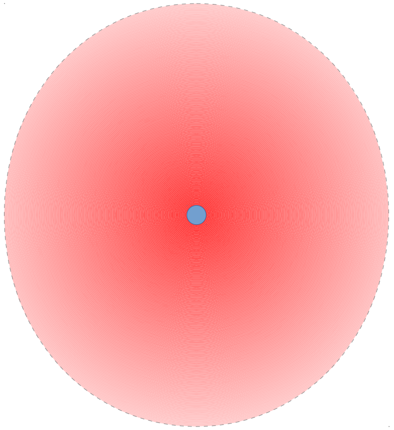


The First Black Box

Particle Interactions with Matter



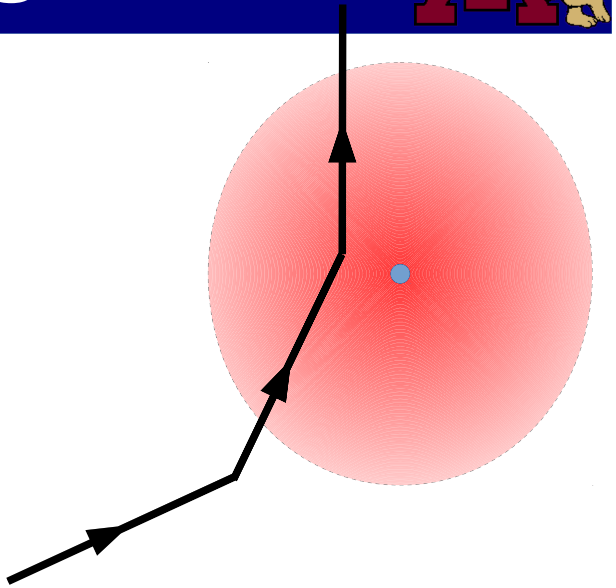
Targets and Interactions



- Matter is a diffuse cloud of electrons with a distribution of small, high q, high mass, nuclei
- The interactions between the incoming particles and the target will determine how the N daughter particles are created
  - Electromagnetic interaction
    - Radiative interactions and ionization-type interactions
  - Strong interaction
- Which interactions have the largest cross sections and what are the relevant length scales that result?

Radiative Interactions

- Cross-section is set by classical electron radius and a photon propagator integral over the unscreened nuclear charge
  - Electromagnetic radiative interactions will occur dominantly at low momentum (photon propagator $1/q^2$) and in regions with coherent non-zero net charge (near the nucleus)



$$\sigma_{radiative} \approx \pi r_e^2 \left[\left(\frac{\alpha}{\pi}\right) Z^2 \int_{1/r^2_{atom}}^{1/r^2_{nucleus}} \frac{dq^2}{q^2} \right]$$

$$\sigma_{radiative} \approx 4 \alpha r_e^2 Z^2 \ln\left(\frac{r_{atom}}{r_{nucleus}}\right)$$

$$\sigma_{radiative} \approx 4 \alpha r_e^2 Z^2 \ln\left(\frac{183}{\sqrt[3]{Z}}\right)$$

Mean Free Path

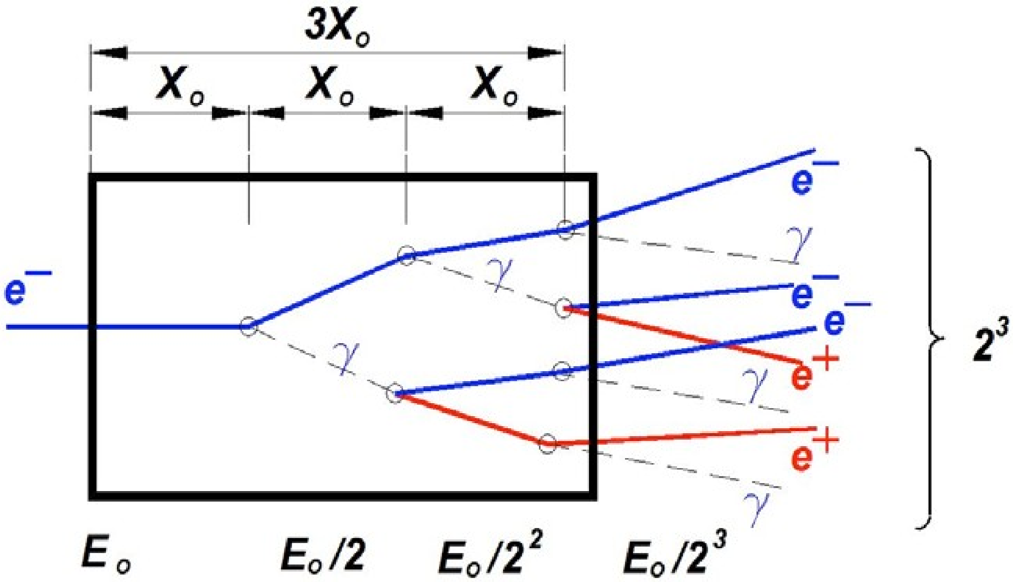
- What is the mean free path for an electron?

$$MFP = X_0 = \frac{1}{n\sigma}$$

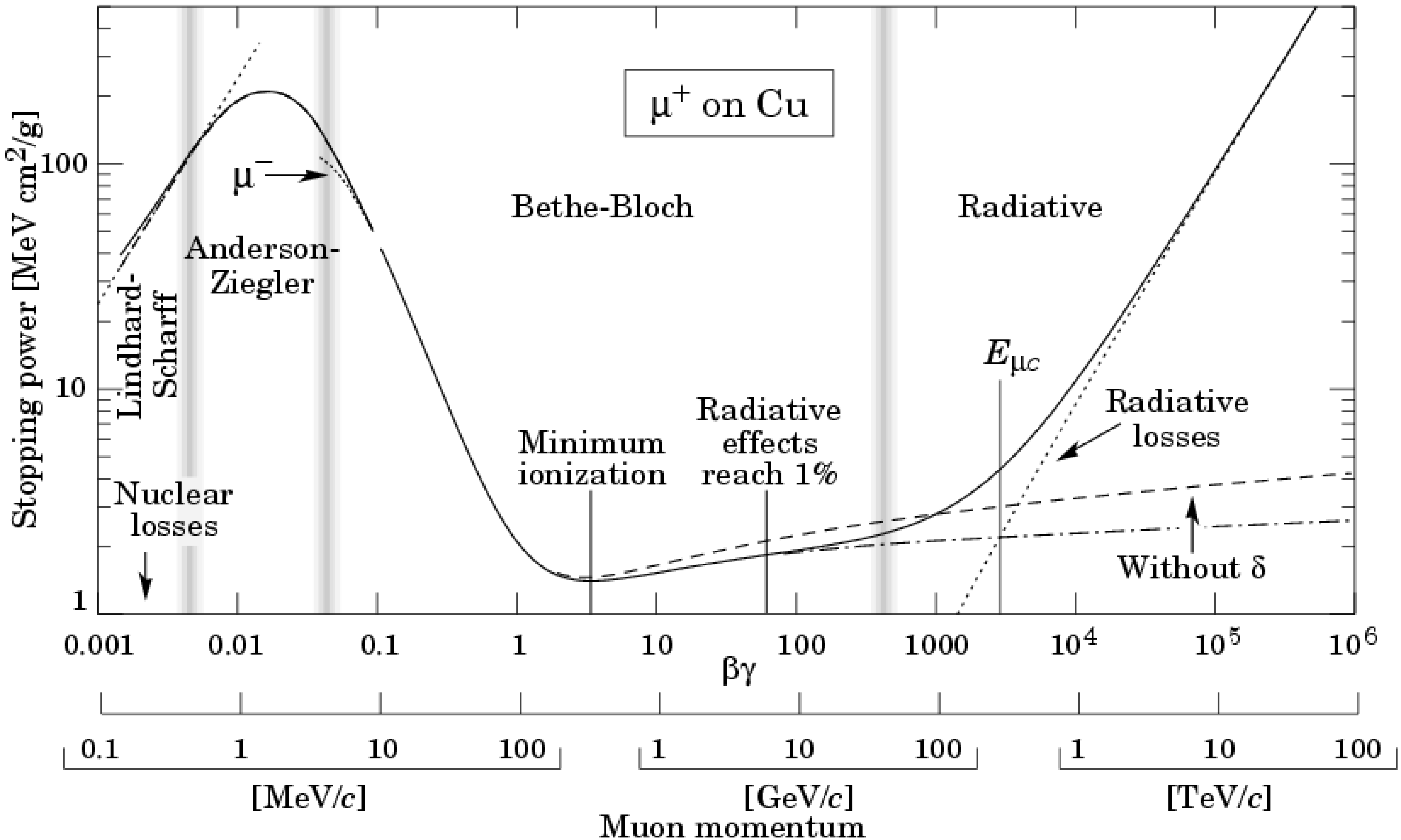
$$X_0 = \frac{1}{4 n \alpha r_e^2 Z^2 \ln \frac{183}{\sqrt[3]{Z}}}$$

- Photon radiation length: $X_0^\gamma = \frac{9}{7} X_0$

Electron Shower in a thin absorber



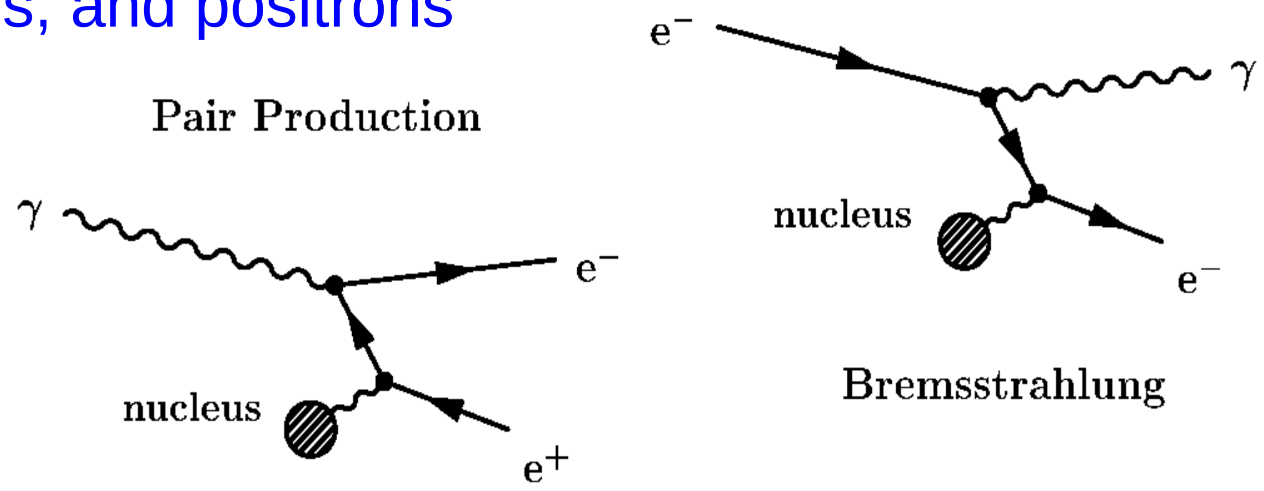
When not showering...



- In between radiative interactions, charged particles will have ionizing interations, Compton-scatters, and similar low-momentum-transfer interactions

Electromagnetic Shower Development

- In the first radiation lengths of a shower, radiative processes dominate, resulting in a large multiplication of photons, electrons, and positrons

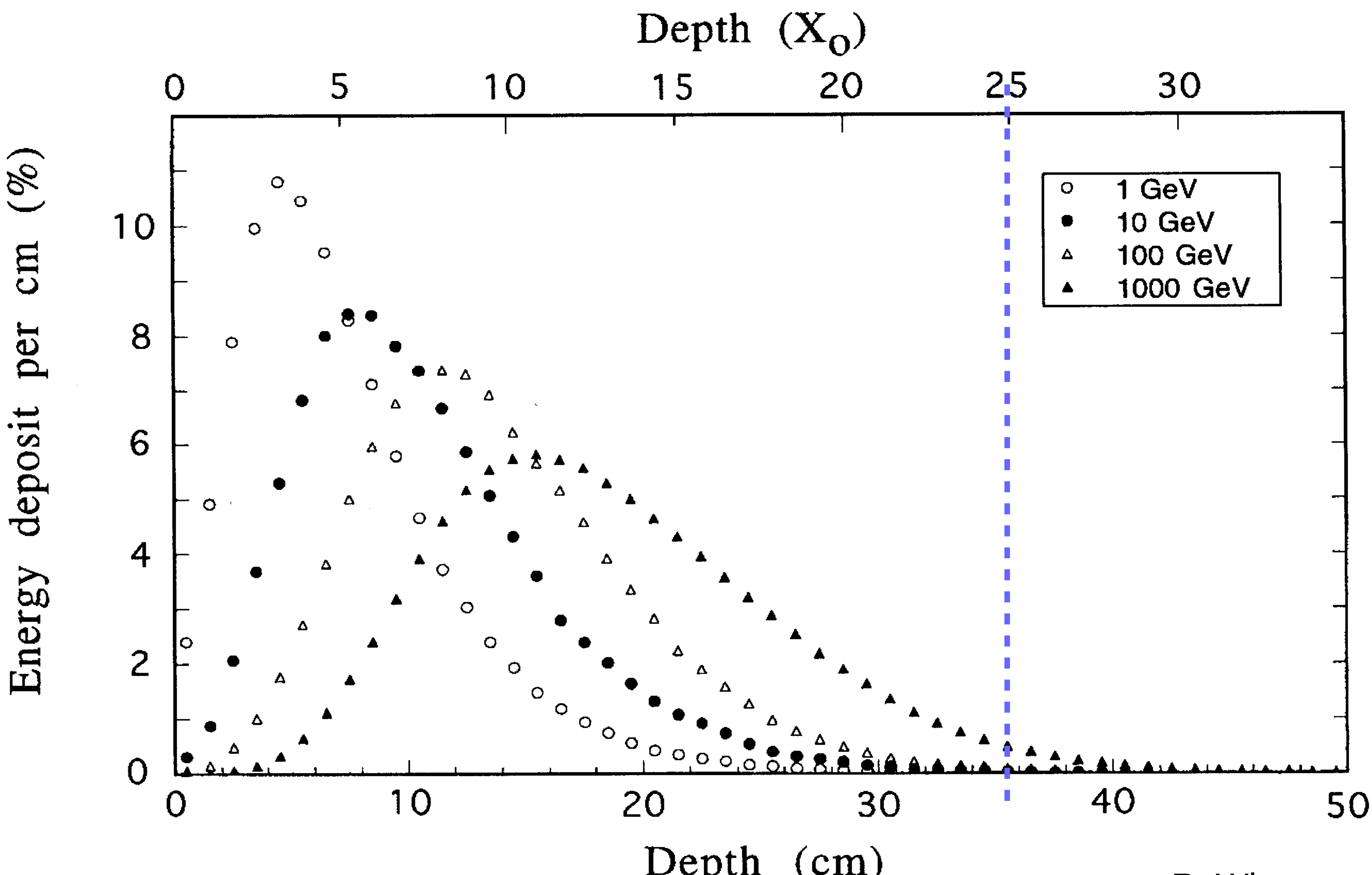


- As the average particle energy drops, Compton scattering, photoelectric, and ionization processes dominate
  - In the final count of particles, there 100x as many liberated atomic electrons as positrons
- Finally, particle energies fall to the point where they are absorbed in atomic systems and the density of particles starts to fall

Shower Max

- At the shower maximum, the amplification rate becomes unity. "Shower max" is the plane in the shower development which has the largest number of particles flowing through it.
  - Average particle energy: E_c (Pb = 7.2 MeV, Fe = 22 MeV)
  - Number of particles : $N_{max} = E_i/E_c$
  - Location of shower max : $L_{max} \sim \ln (E_i/E_c)\, X_0$
  - Total path length of particles : $L_{tot} \sim N_{max}\, X_0/\ln 2$
- Energy of the initial particle can be determined from N_{max} or L_{tot} (which is proportional to N_{max})

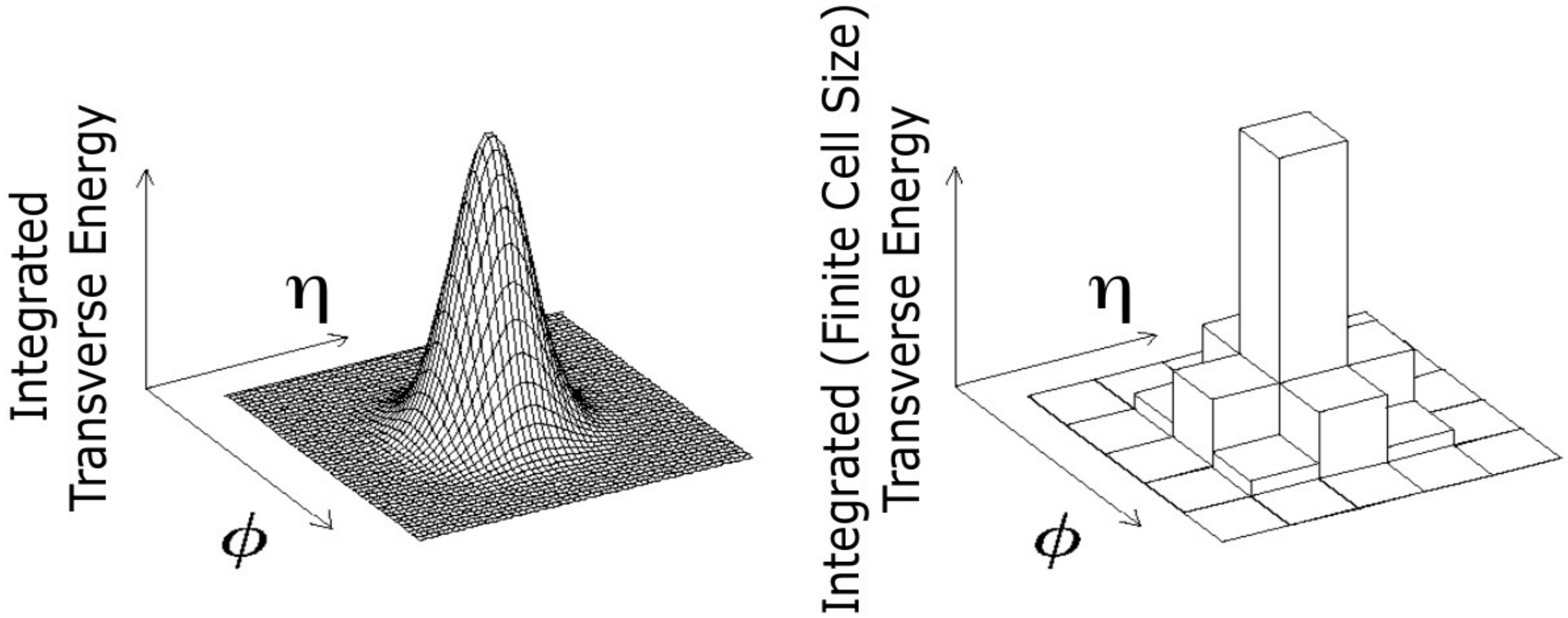
Shower Profile (Cu)



R. Wigmans

Transverse Shower Profile

- Moliere radius: characteristic transverse size of an electromagnetic shower
  - $r_m = (21\ \mathrm{MeV}/E_c)\ X_0$
- Calorimeter transverse segmentation should be somewhat finer than Moliere radius
  - Using energy distribution in neighboring cells, shower position with the peak cell can be determined to within 5% of the cell size



What about muons and hadrons?

- Radiative processes are suppressed by m^{-2} for muons and protons
  - Additional suppression for pions

$$\sigma_{radiative} \approx 4\alpha r_e^2 Z^2 \ln\left(\frac{183}{\sqrt[3]{Z}}\right)$$

$$r_e \propto \frac{1}{m_e}$$

$$\frac{\sigma^f_{radiative}}{\sigma^e_{radiative}} = \left(\frac{m_e}{m_f}\right)^2$$

- For hadrons, strong interactions are more important
  - σ(pp) ~ 40 mb and ~constant with q^2
  - σ(πp) ~ 26 mb [2/3 σ(pp)]

$$\lambda_{int} = \frac{1}{n A^{2/3} \sigma(pp)}$$

- Wide array of processes with different rates
  - Pion production, nuclear fission, neutron capture, nucleus excitation...

Hadron calorimetry is complex!

Material Properties

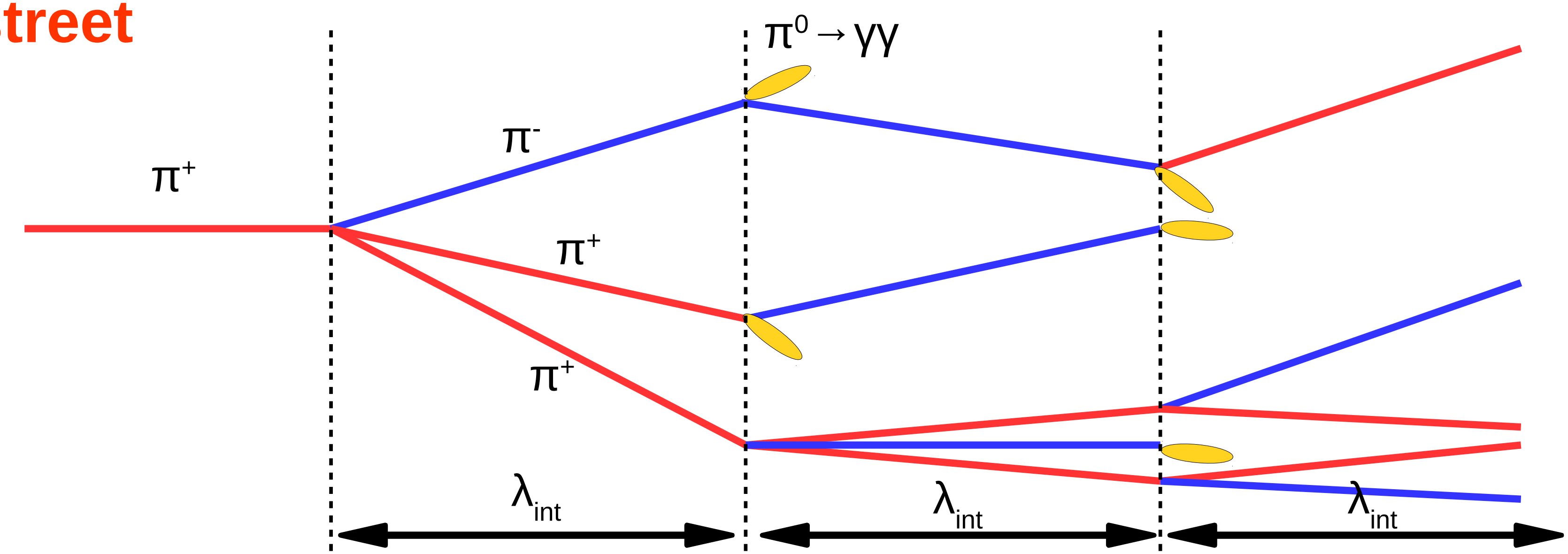
Material	Z	Density [g/cm^3]	X_0 [cm]	λ_{int} [cm]	E_c [MeV]
Fe	26	7.9	1.8	17	22
Cu	29	9.0	1.4	15	19
Pb	82	11	0.6	17	7.6
W	74	19	0.4	9.6	8.1
U	92	19	0.3	11	6.5
Plastic	~2	1.0	42	80	~92
Liquid Argon	18	1.4	14	84	32
Quartz	~10	2.3	12	43	44
Si	14	2.3	9.4	46	40
Al	13	27	8.9	39	42

Pion Cascade

- Primary pion interaction with nuclei is

$$\pi + N \rightarrow a\pi^{+} + b\pi^{-} + c\pi^{0} + X$$

  - No requirement for charge conservation (charge exchange with nucleons)
  - Equal amounts of π^{+}, π^{-}, π^{0} produced on average
  - When a neutral pion is produced, it rapidly decays to two photons and initiates an electromagnetic shower: **one-way street**



f_{EM}

- In the simplest model, 2/3 of the energy goes into electromagnetic energy at each stage

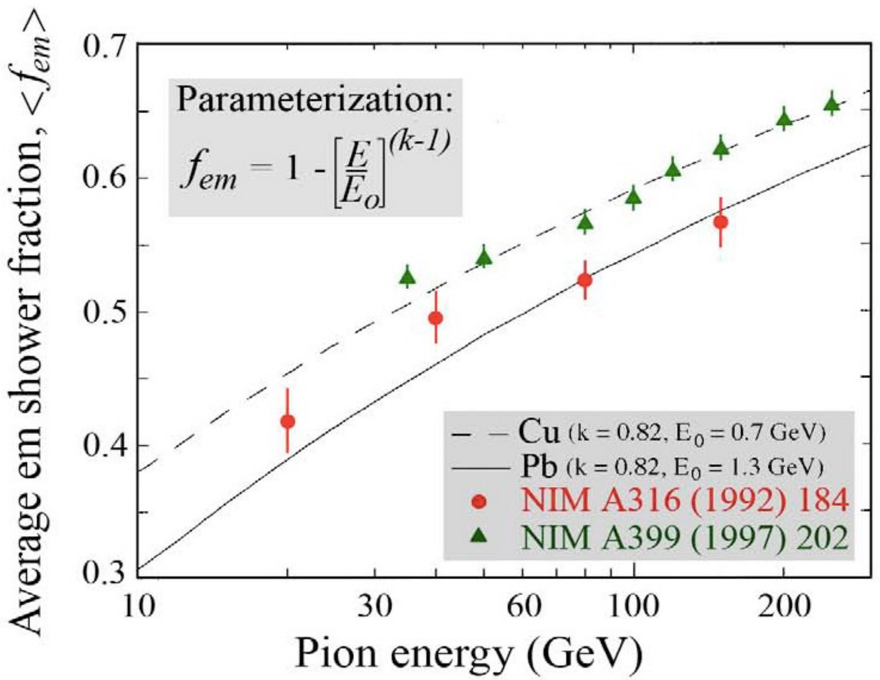
$$f_{em}=1-\left(\frac{2}{3}\right)^{E/E_0}$$

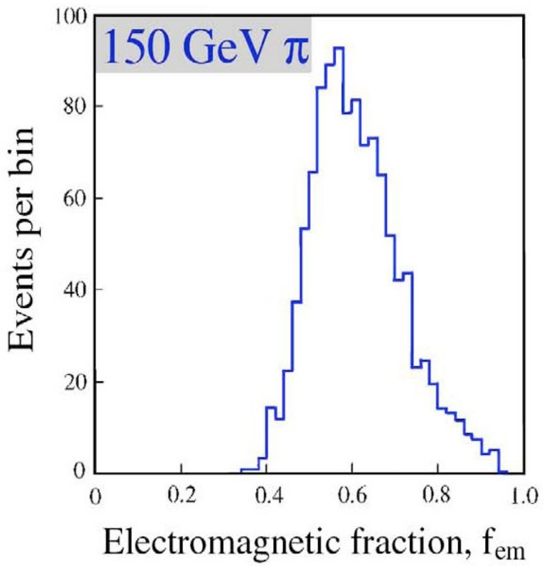
  - The electromagnetic energy fraction increases as the initial energy increases

- Since other processes are present, a more-complex model fits better:

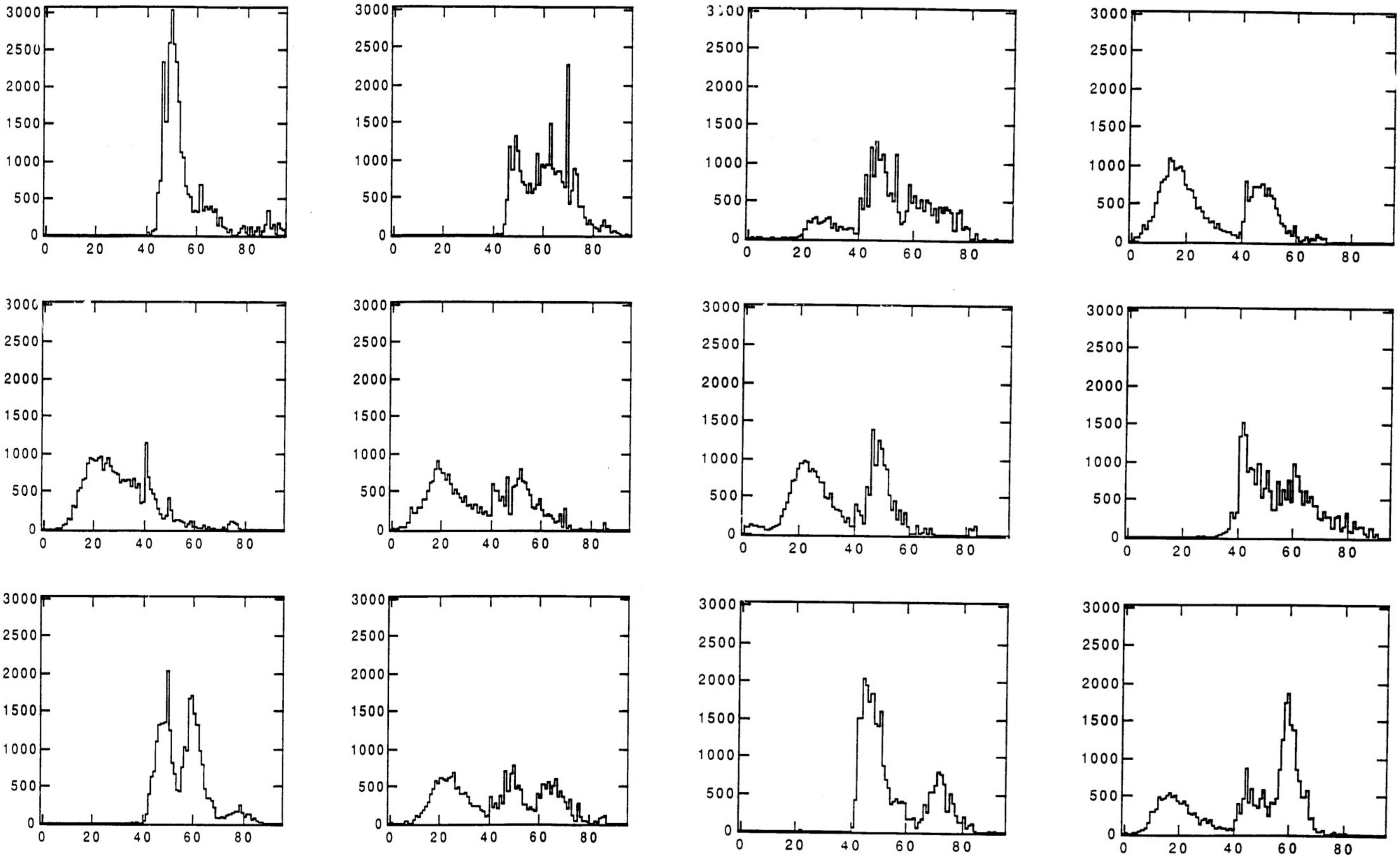
$$f_{em}=1-\left(\frac{E}{E_0}\right)^{k-1}$$

  - And there are fluctuations!





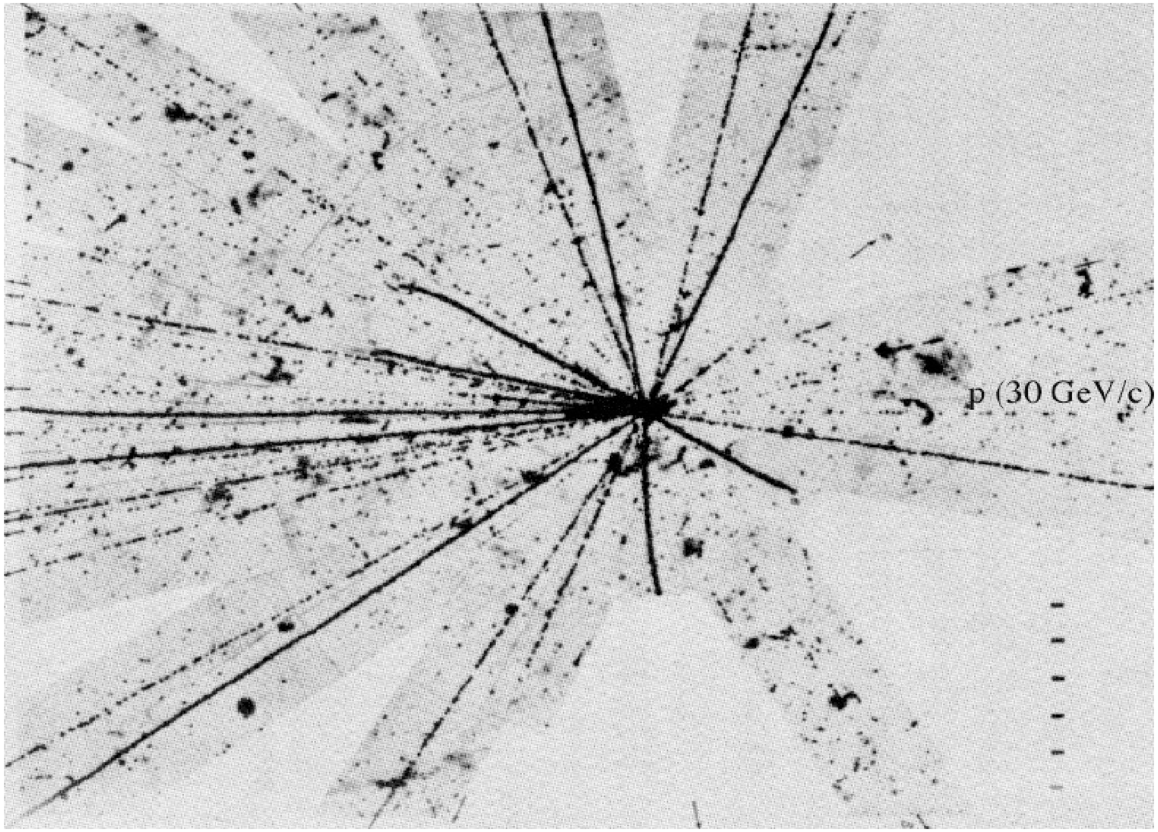
Hadron-Shower Fluctuations



270 GeV pions

Where does the energy go?

- For the hadronic part of the shower, energy goes into both visible and invisible places
  - O(60%) : Ionizing particles (protons, pions : visible)
  - O(10%) : Evaporation neutrons (somewhat visible, sometimes late)
  - O(30%) : Nuclear binding energy and recoil (invisible)



Nuclear “star” initiated by 30 GeV proton, as observed in photographic emulsion

^{237}U is created by high-energy photon interactions (π^0 in core of shower)

Mo is created by fission events initiated by MeV neutrons

^{239}Np is created by capture of thermal neutrons

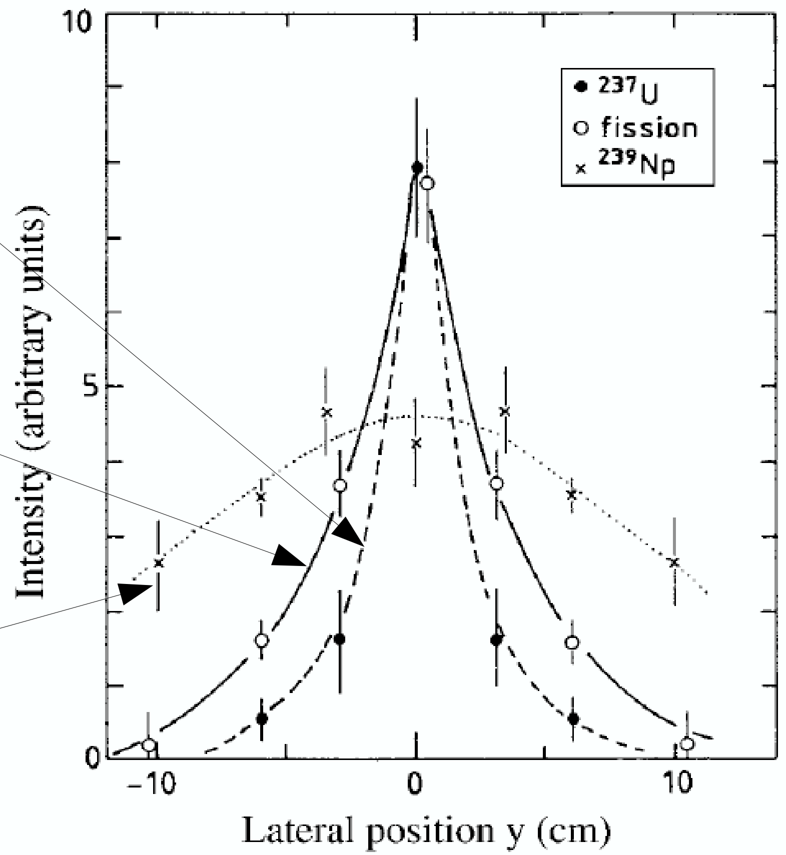
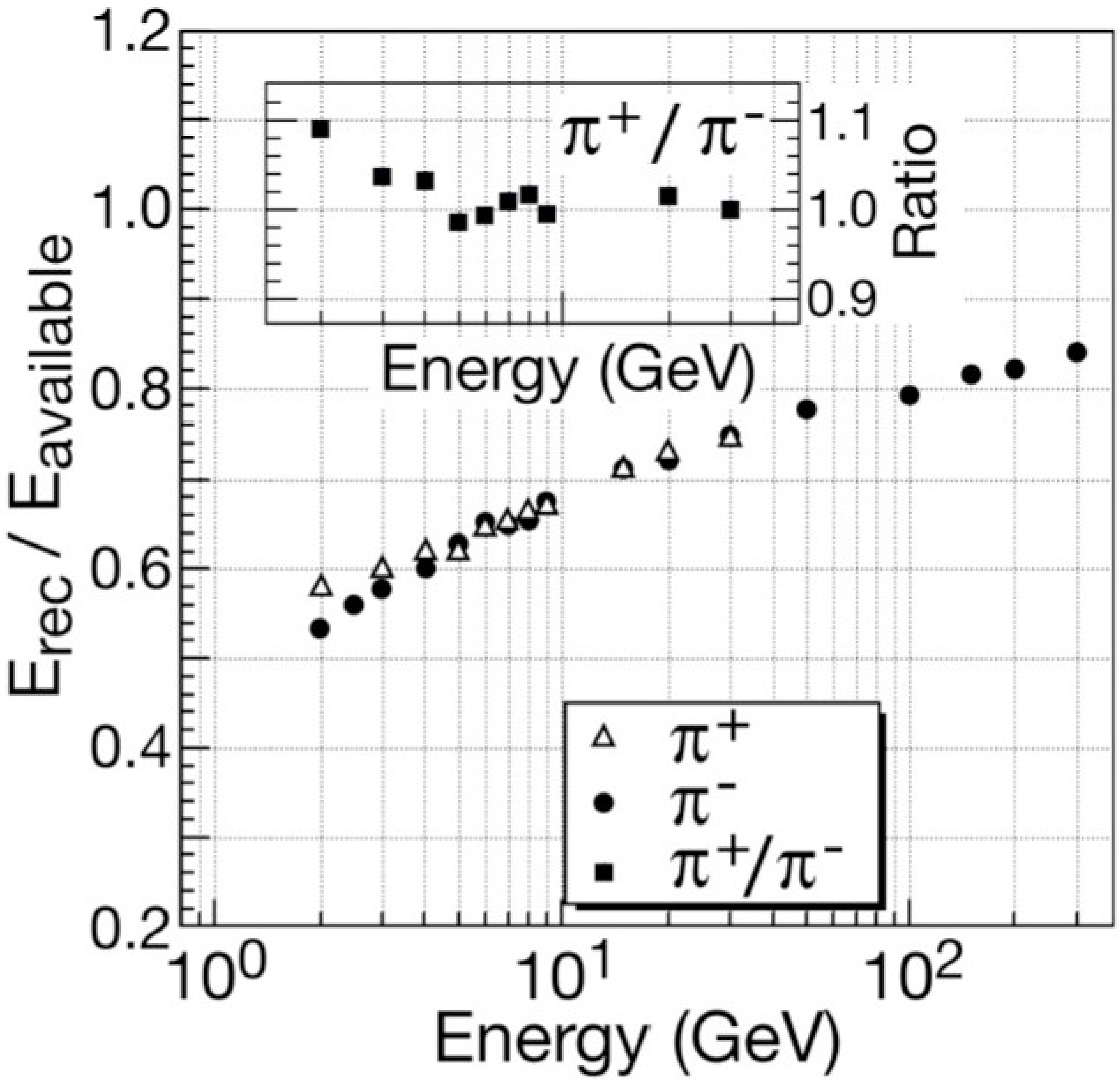


FIG. 2.34. Lateral profiles for 300 GeV π^- interactions in a block of uranium, measured from the induced radioactivity at a depth of $4\lambda_{int}$ inside the block. The ordinate indicates the decay rate of different radioactive nuclides, produced in nuclear reactions by different types of shower particles. Data from [Ler 86].

f_{EM} and invisible energy

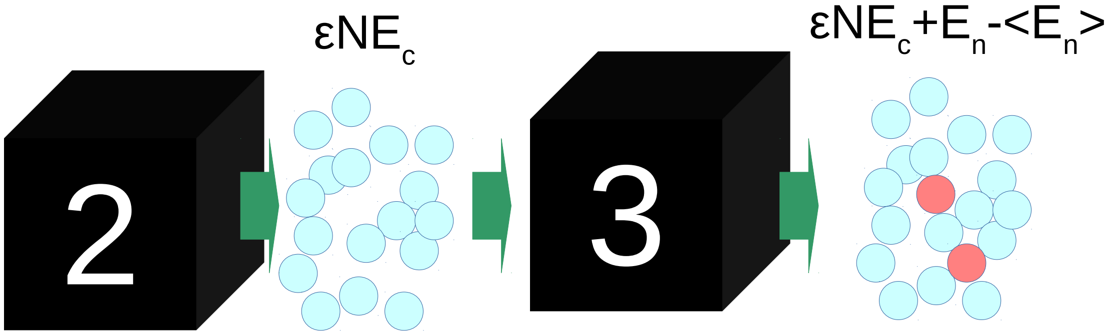


- As the f_{EM} rises, the fraction of energy lost invisibly will decrease
- As there are more neutrons than protons in heavy nuclei, π^+ will convert into π^0 more efficiently than π^-

$$\pi^+ n \rightarrow \pi^0 p$$
$$\pi^- p \rightarrow \pi^0 n$$

The Second and Third Black Boxes

Measuring the particles produced



Principle of Measurement

- The basic principle of measurement in calorimetry is to determine the total number or path length of particles produced in the shower
  - Subject to ~linear proportionality (e.g. charged particles only or a fixed nominal fraction of the path lengths)

$$\frac{\sigma_{E_m}}{E_m} = \frac{a}{E_m} \oplus \frac{b}{\sqrt{E_m}} \oplus c$$

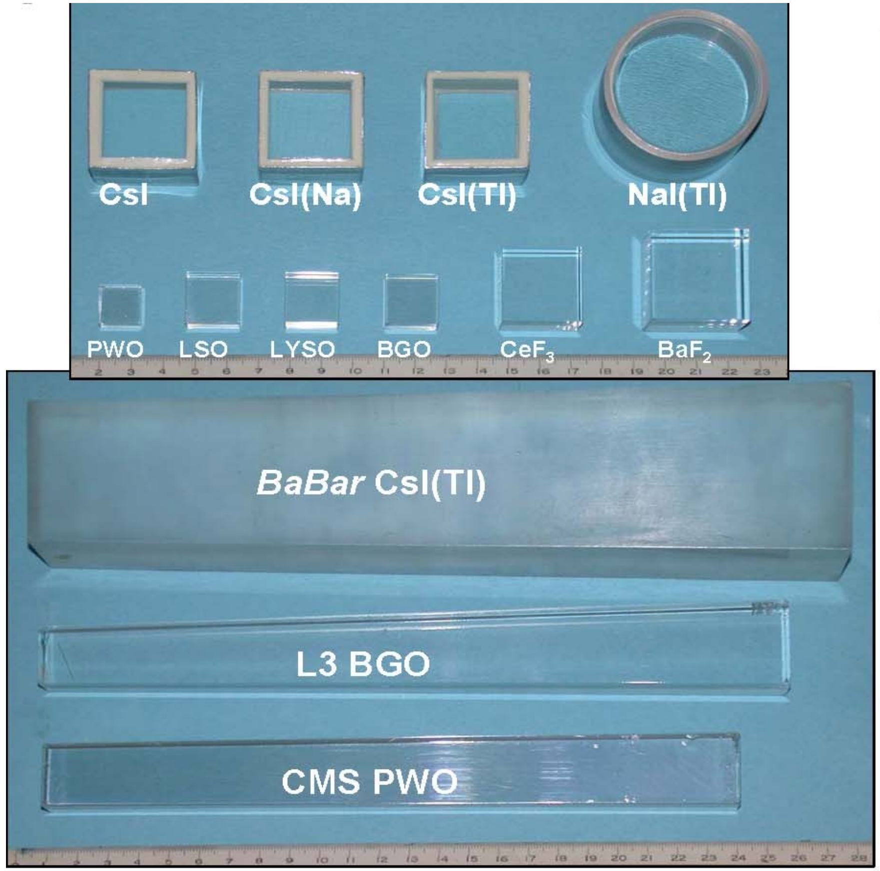
Noise term, fixed scale in energy, important at low energy or when adding many channels

“Stocastic” term, set primarily by counting statistics and other sources of random fluctuation

“Constant” term due to effects which are proportional to energy such as miscalibration and detector nonuniformities

Total absorption calorimetry

- Transparent crystals including a heavy element in the matrix



1.5 X_0 Samples:

Hygroscopic Halides

Non-hygroscopic

Full Size Crystals:

BaBar CsI(Tl): 16 X_0

L3 BGO: 22 X_0

CMS PWO(Y): 26 X_0

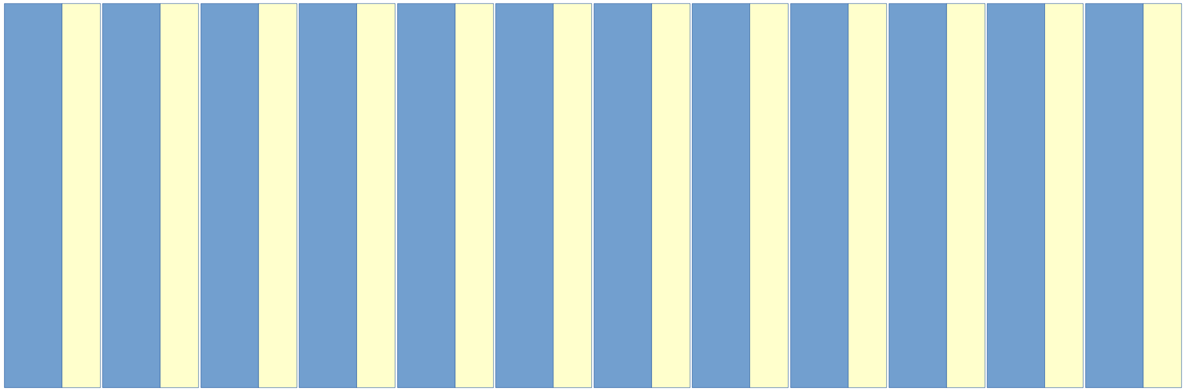
- A fraction of ionization energy will produce visible light through scintillation
    - Measurement of the amount of light produces the energy measurement => requirement for a photodetector

Resolution Calculation

- For a 1 GeV photon using CMS's $PbWO_4$
  - ~100,000 photons/GeV => 0.3%
- Not all photons are detected – many are absorbed before reaching the photodetector or do not produce a signal
  - 4% of photons become PE (4000) => 1.6%
- Fluctuations in the photodetector generate an additional factor of √2 1.6%*2 => 2.2%
- Limit the lateral sum to keep the number of channels contributing to the electronic noise to 25, the containment fluctuations add 1.5% in quadrature

=> 2.7%

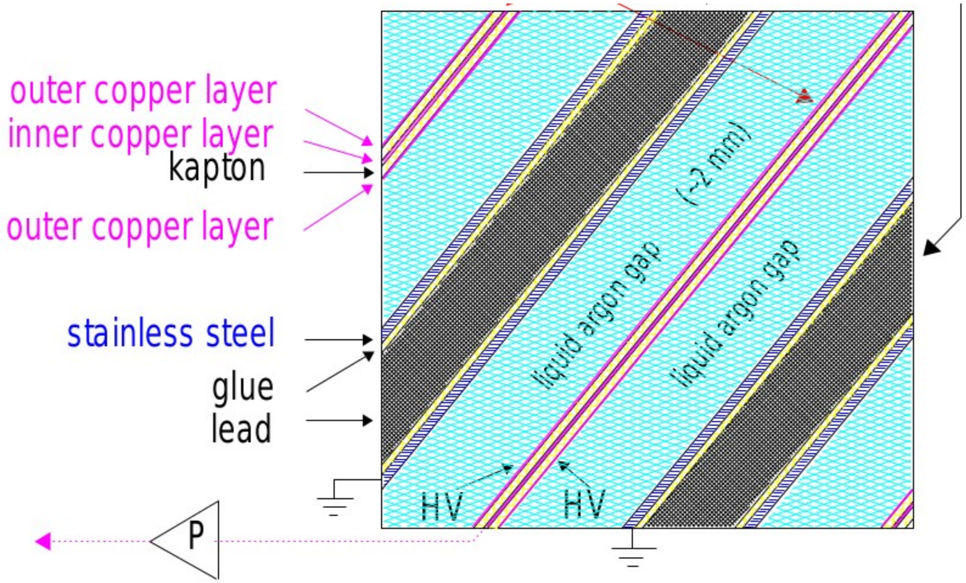
Sampling Calorimetry



- Materials appropriate for total-absorption calorimetry are very expensive
  - Financially impossible for hadron calorimetry!
- Alternative: separate the roles of a cheap dense material for shower development and a lighter material for signal measurement

Resolution in a sampling calorimeter

- To first order, energy loss is entirely within the absorber, with the active material counting the number of produced secondaries.



- ATLAS electromagnetic calorimeter is a sampling calorimeter with lead as the primary absorber and liquid argon as the active material
- For lead, E_c=7.8 MeV, so a 1 GeV electron will produce an average of 128 secondaries. Each lead layer has a width of X0/3, resulting in three measurements of each final secondary

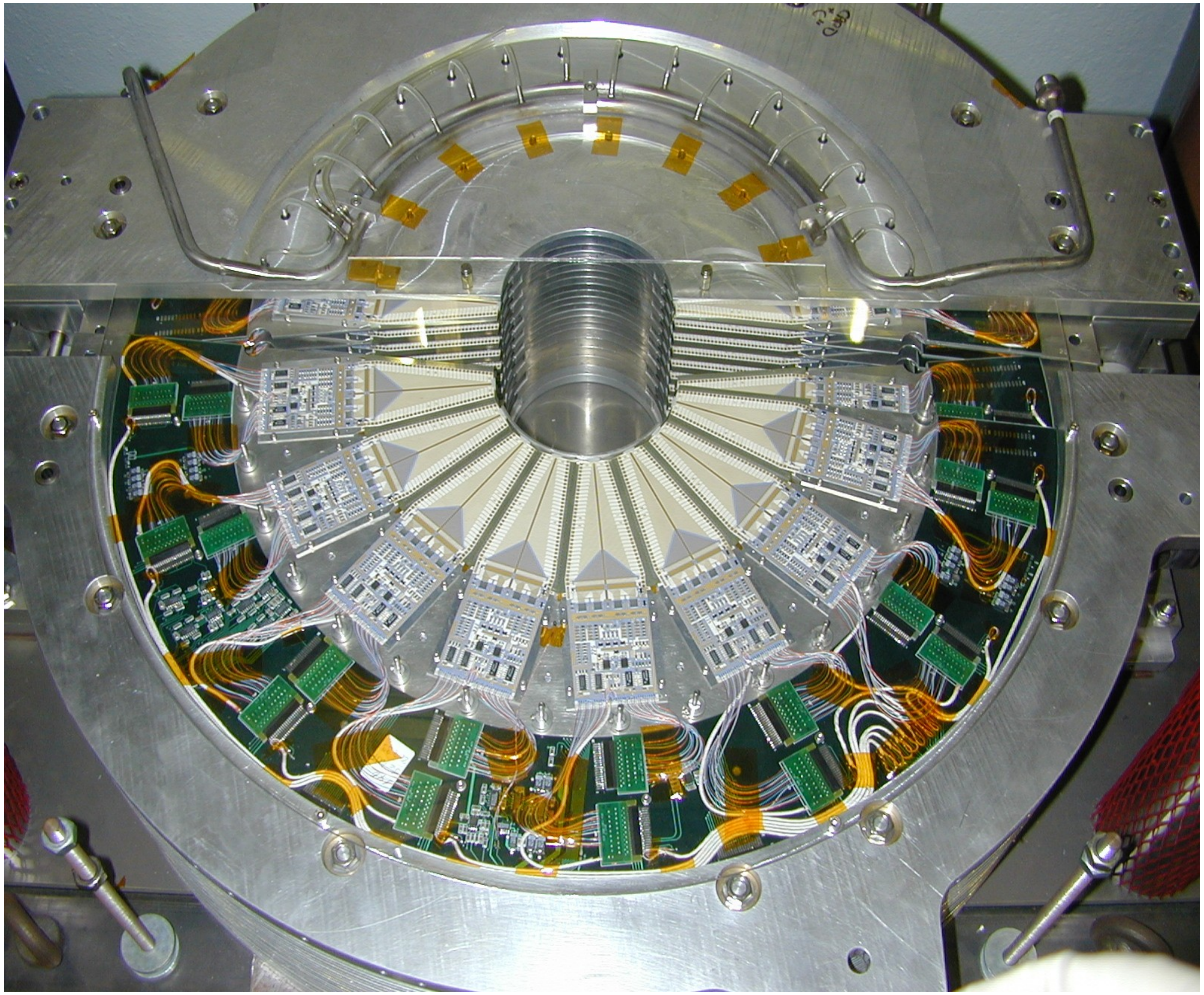
$$\sigma_{min}=\frac{1}{\sqrt{384}}=5.1\%$$

Additional effects raise resolution to 10%

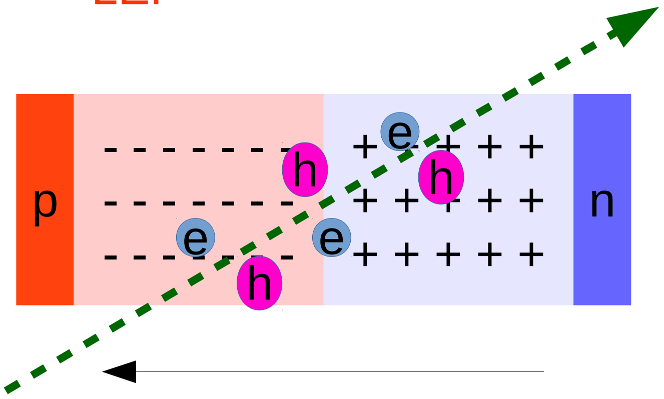
Tools for building a calorimeter

- Modern HEP detectors use electronics to collect and process data (e.g. triggering)
- Active materials
  - Noble liquids and silicon sensors allow direct collection of ionziation charge
  - Crystals, plastic and liquid scintillators produce light
  - Cerenkov radiation can also be used
- Light-handling tools
  - Phototransducers: conversion of visible and near-visible light into electrical signals
  - Photon collection hardware

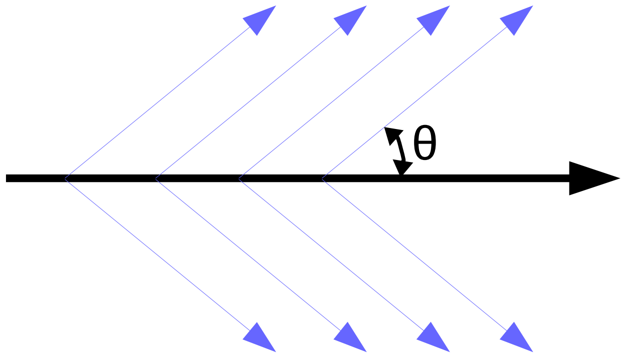
Silicon-based Calorimetry



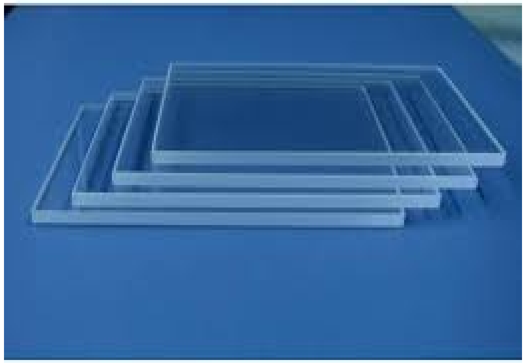
- Charged particles passing through a silicon diode will produce electron/hole pairs which will be swept apart by the strong electric fields in the diode and can be collected to determine the fluence
  - Silicon/tungsten calorimeters were used extensively for luminosity measurements at LEP



Cherenkov Radiation

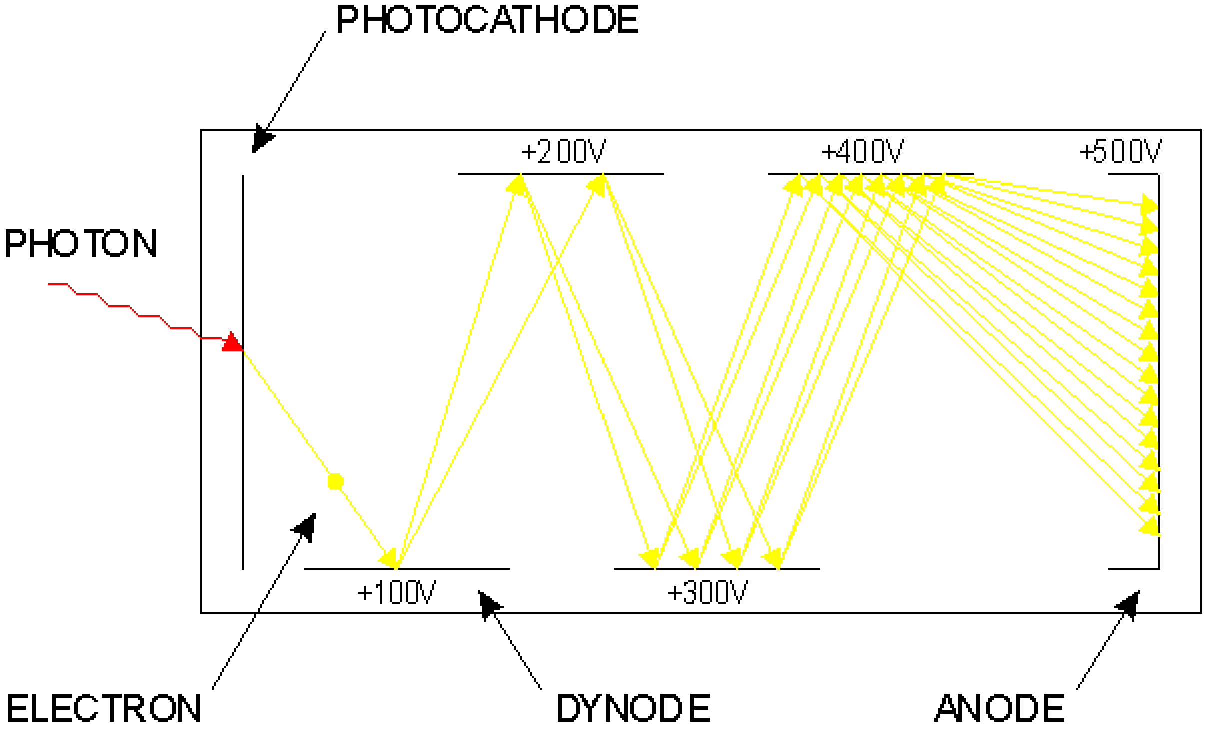


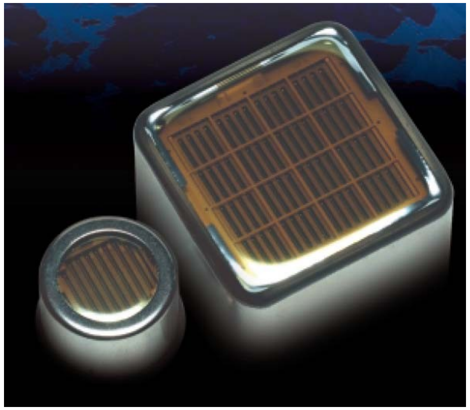
$$\cos\theta = \frac{c}{v\,n}$$



- Cherenkov radiation is produced when a charged particle passes through a medium at faster than the local speed of light
    - Used as a particle identification technique comparing *v* and *p* to determine *m*
- For calorimetry, generally only electrons are relevant.
    - For quartz (n=1.485), minimum KE_e=0.1 MeV, minimum KE_p=220 MeV
    - Cerenkov calorimeters count the path length of high-energy electrons in showers : very non-linear response for hadrons

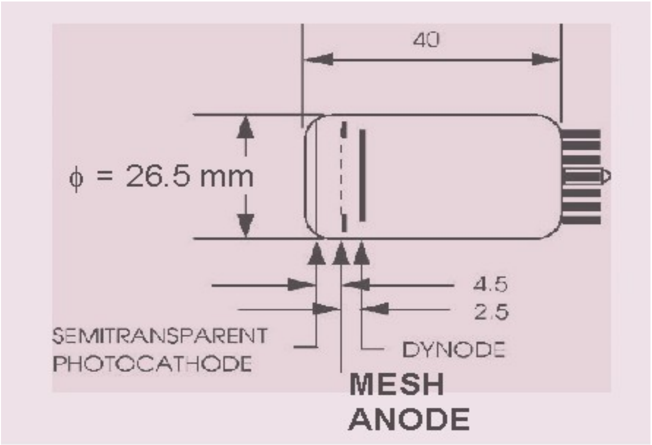
High Voltage Devices





Photomultiplier Tube

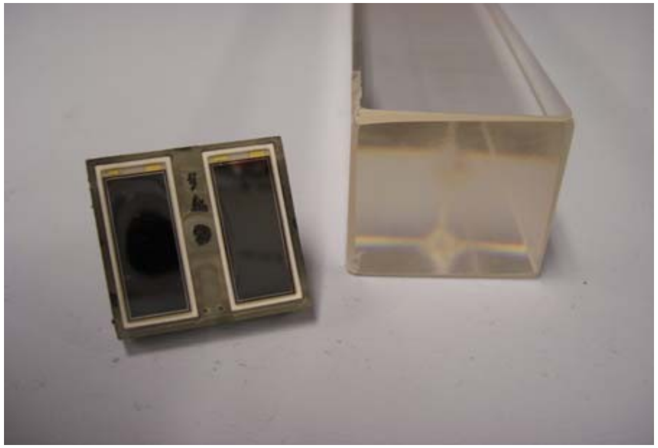
Internal gain 10^4-10^7, very sensitive to magnetic fields, requires O(1kV) power supply, small sensitivity to radiation, moderate PDE (<50%)

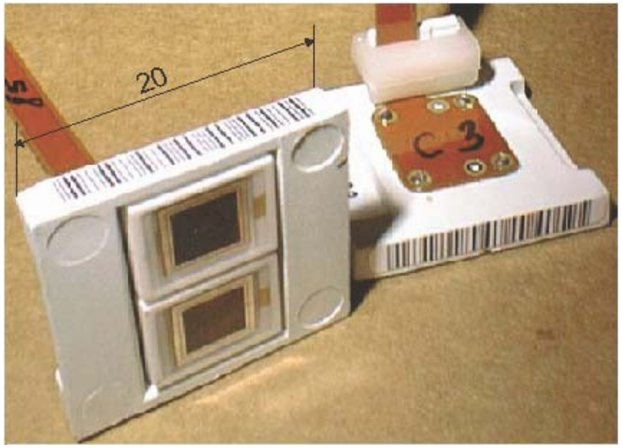


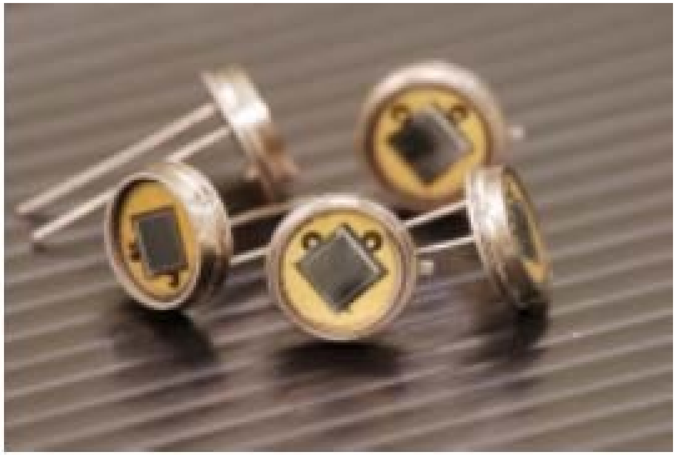
Vacuum phototriode

Internal gain 5-15, can operate in magnetic field parallel to device body, requires O(1kV) power supply, PDE <20%

Silicon Phototransducers



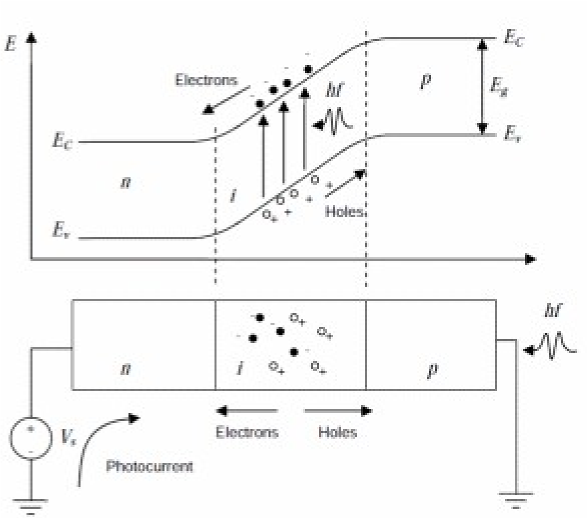


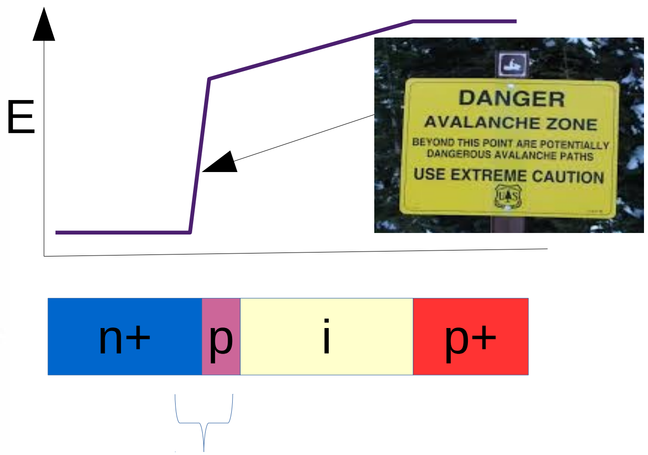


PIN diode
No internal gain, robust to magnetic fields, moderate sensitivity to radiation, PDE up to 90%+

Avalanche Photodiode
Internal gain 50-1000, robust to magnetic fields, sensitive to highly-ionizing radiation, PDE ~80%

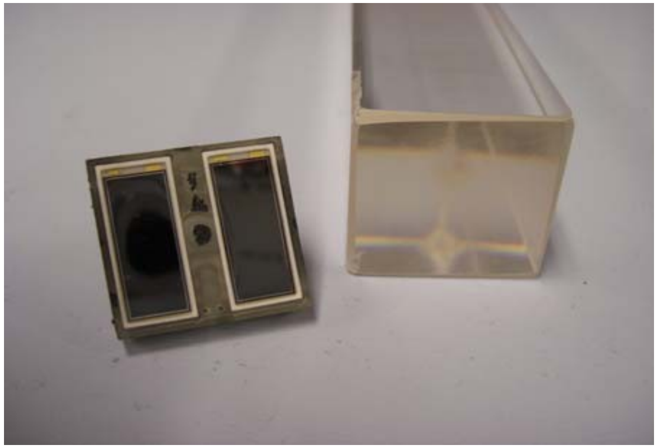
SiPM/MPPC
Internal gain 10^4 - 10^7, robust to magnetic fields, limited radiation sensitivity, linearity determined by pixel count, PDE 20%-50%

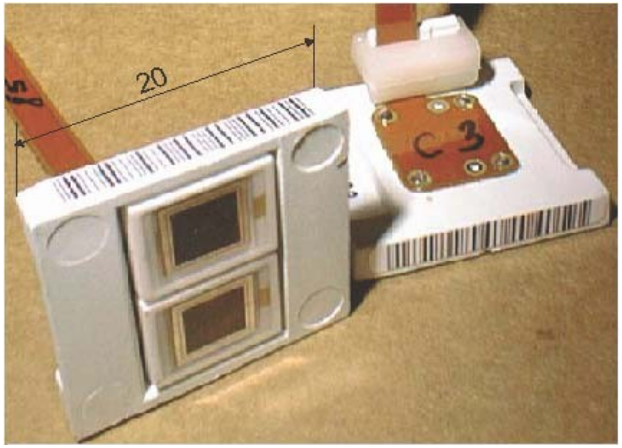


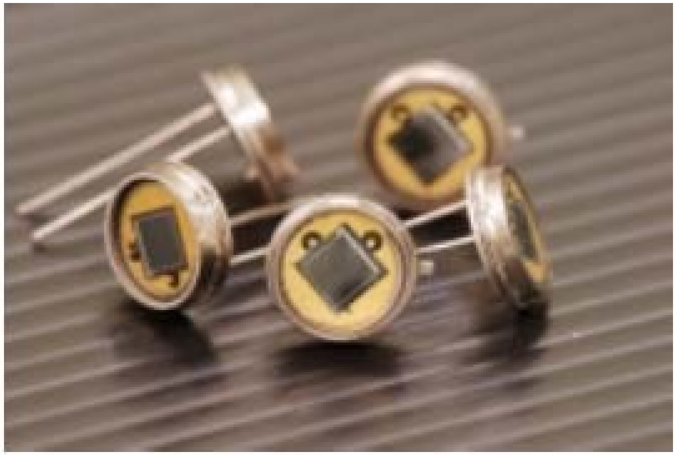


Avalanche zone

Silicon Phototransducers







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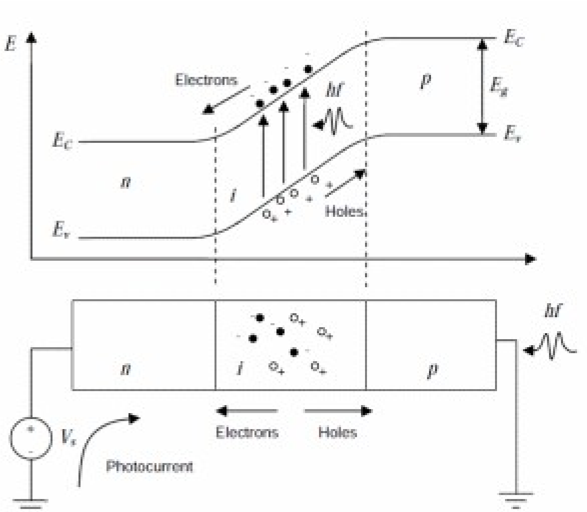
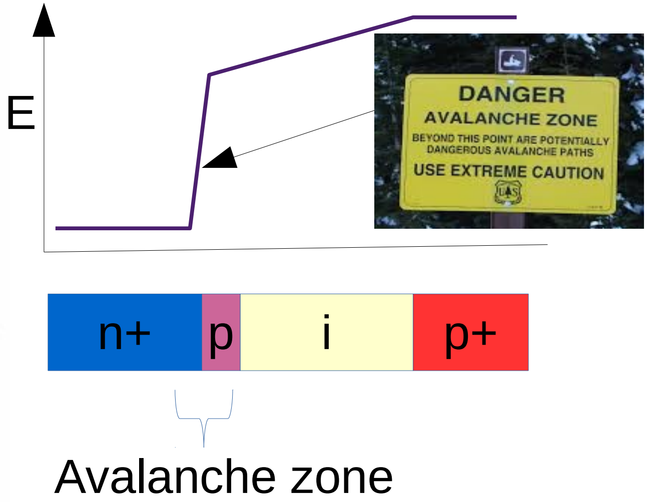
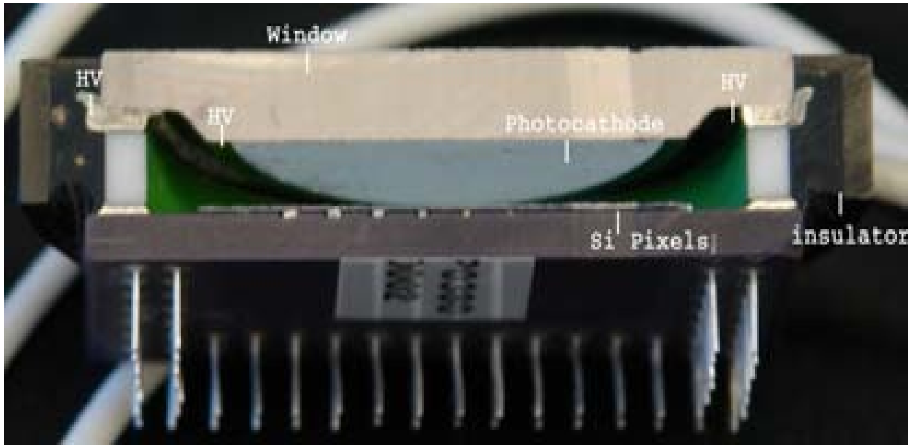
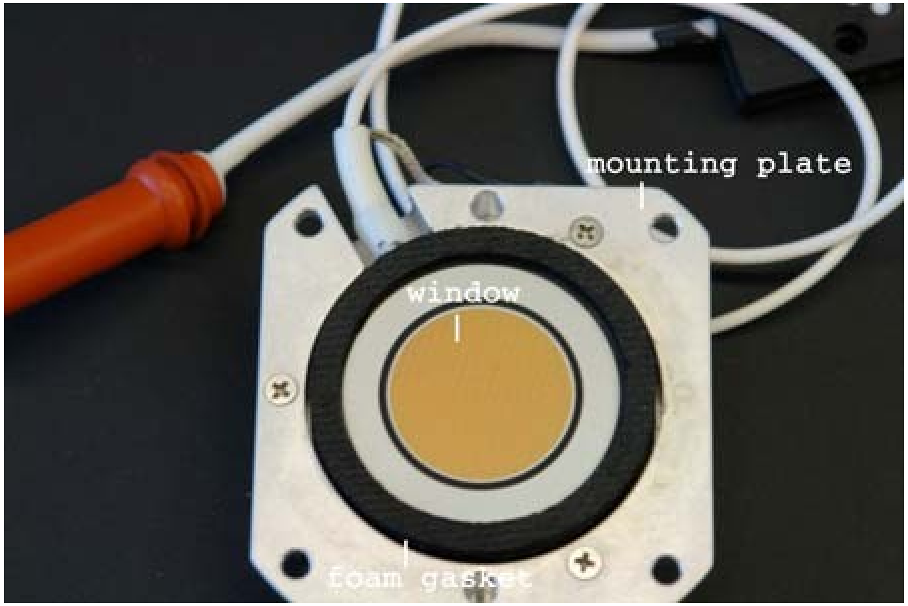
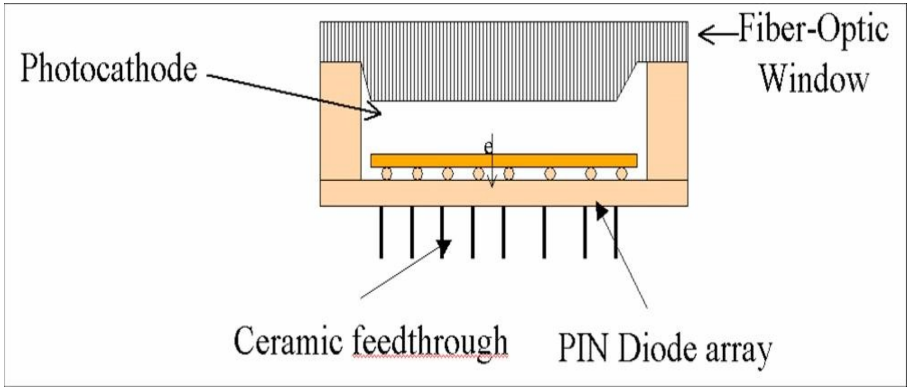




Hybrid Device: HPD



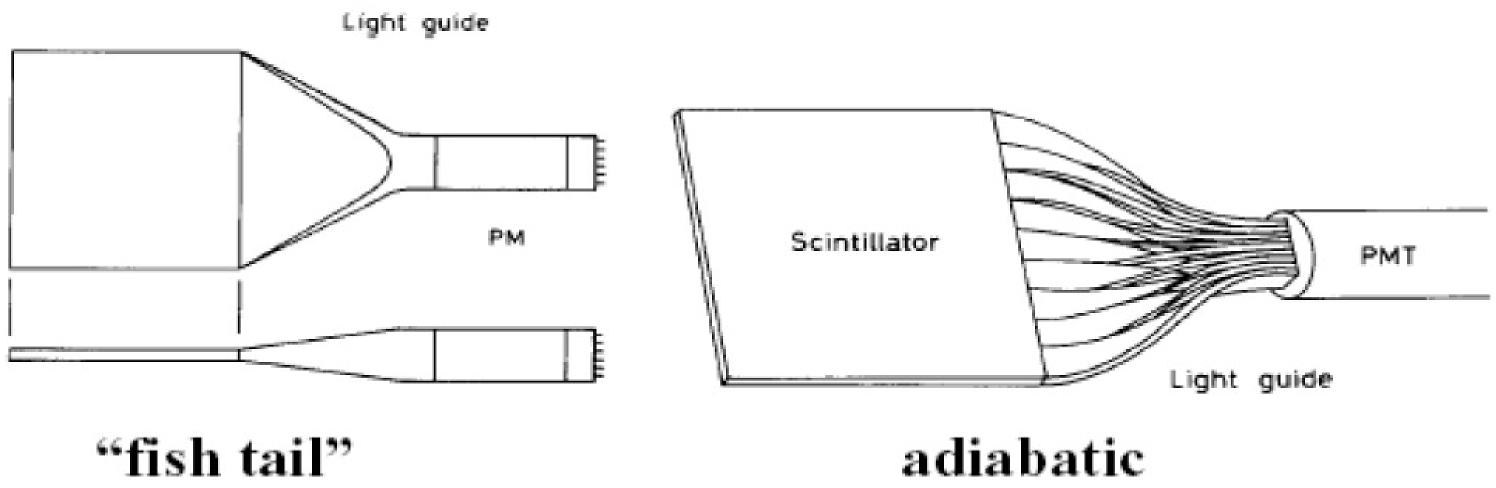




HPD
Internal gain ~2000, can be operated in magnetic fields parallel to electric field
Requires O(8000V) over gap of ~4 mm (2 MV/m)

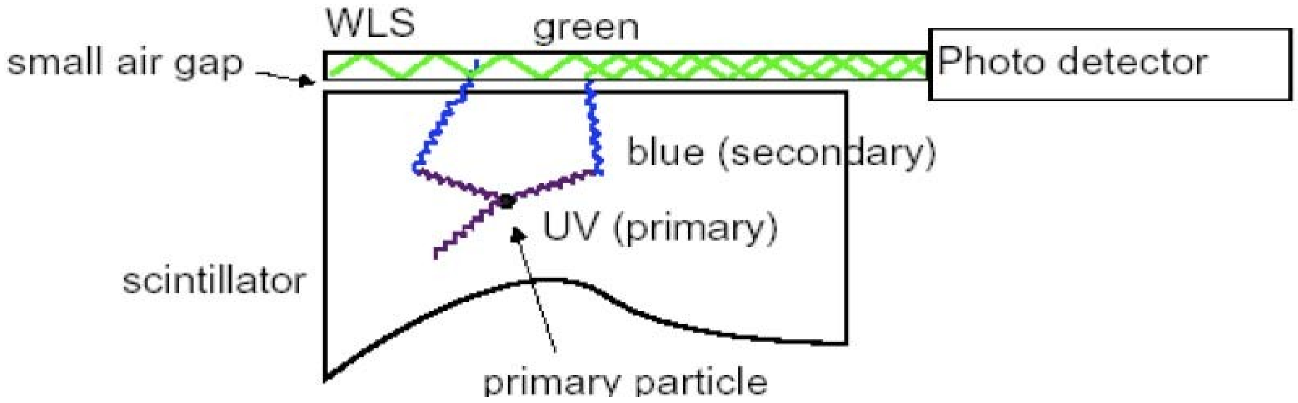
Light-Handling Tools

- Light in scintillators is produced isotropically, which makes it hard to concentrate onto the (expensive) area of a photodetector
  - Lagrange invarient: $A_1\Omega_1=A_2\Omega_2$
- Elegant light-guide designs have been produced over the years to transfer the maximum surface area from a scintillator plane to a phototube



Cheating Lagrange

- Particularly for hermetic colliders detectors, light guides and phototubes are problematic
- If the wavelength of the light is increased (energy is lost), the Lagrange invarient does not apply
- Use of wavelength-shifting systems (particularly “WLS” fibers) is widespread in collider detector design and can allow extreme compression of photodetector area
  - With significant, but uniform, loss of light



Bibliography

- Calorimetry: Energy Measurements in Particle Physics by Richard Wigmans, 2000.
  - Big, verbose, Expensive, but excellent
- The Physics of Particle Detectors by Dan Green, 2005
  - Sufficiently detailed and comprehensive, not just calorimetry, less expensive
- Particle Detectors by Grupen and Shwartz, 2011
  - Nice coverage of historical development and modern devices, not just calorimetry, similar in cost to D. Green book
- Particle Data Booklet
  - Lots of Important Results but Few Explanations, Free!

Tomorrow...

- Tomorrow we are going to bring these elements together to talk about existing and planned calorimeters for LHC and HL-LHC

- Some new issues which we'll touch on:

  - Pileup and event spacing
  - Radiation damage